Evaluation of the Continuous Profiling of Refractive Index Gradients and Humidity Using Wind Profiling Radars

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Introduction

Radar wind profilers are designed to measure the Doppler spectrum of the radial wind along several different beam directions as a function of range [Strauch et al., 1984]. The first moment of the spectrum corresponds to the mean radial velocity of air in the sensing volume, permitting one to calculate horizontal wind speed v and direction, and vertical shear of horizontal wind dv/dz, from range-gated measurements of the off-vertical beams. When the radar beam is directed vertically, the Doppler spectrum can be used to determine not only mean vertical motion w (first moment), but also turbulent vertical velocity fluctuations, through the width (second moment) of the spectrum, These permit C_w^2, the structure parameter of the turbulent vertical velocity field, and ϵ, the turbulent dissipation rate, to be calculated.

Gossard et al. [1982] have shown that wind profiler Doppler spectra contain enough information to compute the vertical gradient of refractivity $d\Phi/dz$, namely,
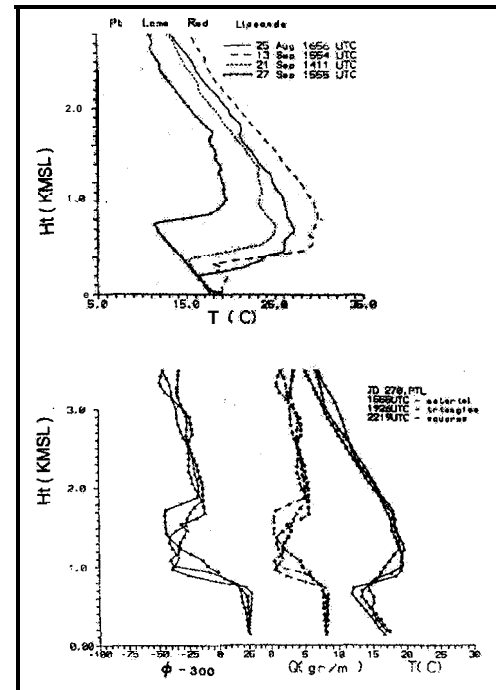

Fig. 1. Typical balloon temperature soundings (above) at Pt. Loma during the experiment, showing strong gradients at various heights. Below are profiles of refractivity, humidity, and temperature computed from successive balloon ascents on Sept. 27, 1995 (Julian Day 270),

$$\left(\frac{d\Phi}{dz}\right)^2 = \left(\frac{L_\Phi}{L_w}\right)^{4/3} \left(\frac{dv}{dz}\right)^2 \frac{C_\Phi^2}{C_w^2}$$

Here Φ is the mean refractivity at level z. The vertical shear of horizontal wind dv/dz is obtained from the radar's first spectral moment while C_Φ^2, the structure parameter of turbulent refractive index fluctuations, is obtained from the zeroth moment (power) of the atmospheric contribution to the Doppler spectra. L_Φ and L_w are the turbulent length scales of refractivity and velocity, respectively.

Previous attempts to calculate these parameters from profilers operating in a high-time-resolution mode were discouraging, primarily because the radar spectra, and hence the spectral moments, are routinely contaminated by aircraft, birds, radio frequency interference, clutter, etc.

In 1994 we tried using manually edited Doppler spectra recorded with ETL's new transportable 449 MHz profiler with much greater success. Editing involves manually deleting false targets prior to calculating spectral moments. Encouraged by these results, in 1995 we collected 449 MHz radar, Radio Acoustic Sounding System (RASS) temperature, and integrated precipitable water vapor (IPW) at Pt. Loma in southern California, near San Diego, during a time when large contrasts in air mass occur, creating large atmospheric gradients to better evaluate the technique.
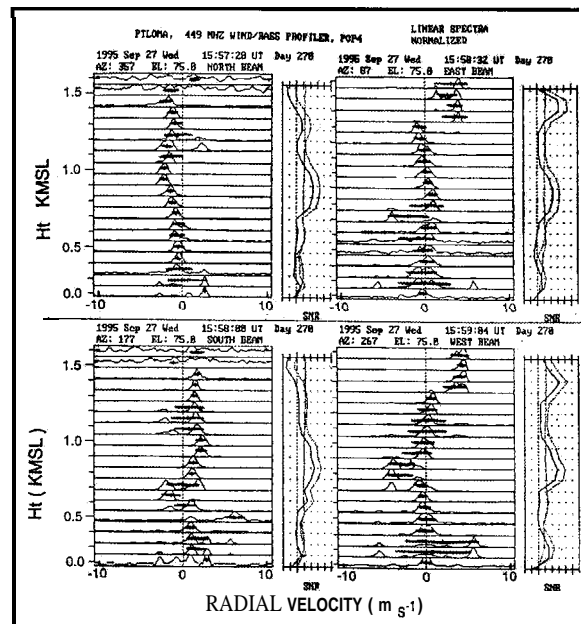

Fig. 2. Range-gated wind profiler spectra for the north, east, south and west beams. Dwell time for each beam was about 33 s. The center of the horizontal line on each spectrum represents the computer-estimated first moment (radial velocity) while the length of the horizontal line is the computer estimate of second moment (velocity spread) in the sensing volume. Unedited, these type of data can lead to errors in wind estimates, particularly at low altitudes.
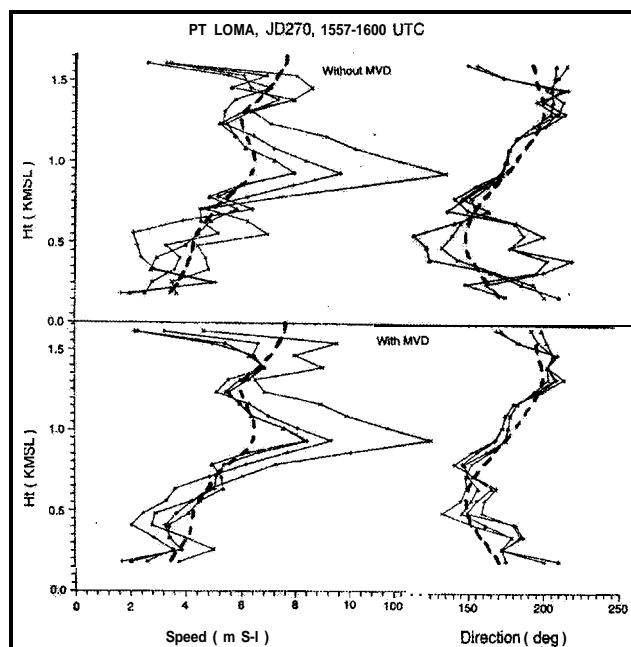

Fig. 3. Wind speed (right) and direction (left) estimates from 5-beam wind profiler data using conventionrd processing algorithms (above) and using Minimization of the Variances of Differences (MVD)(below), for four successive cycles of the radar beams. The balloon sounding made during radar data acquisition is shown by the heavy dashed line.

Pt. Loma Results

Fig. 1 shows typical soundings of temperature obtained from rawinsonde data during the Pt. Loma experiment. To avoid the severe clutter found in the lower range gates we performed our analyses during times when temperature inversions were above 500 m (e.g. Sept. 27, 1995, Julian day 270). Fig. 2 shows range-gated spectra generated by NOAA Aeronomy Laboratory's Profiler On-line Program (POP) for one cycle of four beams. The dwell time for each beam was approximately 33 s. Superimposed on the spectra are horizontal lines indicating the spectral width (second moment) calculated by POP. It is obvious that spectral features not associated with atmospheric winds severely contaminate POP moment products. For this study we manually edited individual spectra to select single spectral peaks that we judged to originate from atmospheric returns.

In addition to manual editing, we applied a new technique called Minimization of the Variance of Differences (MVD) to the off-vertical beams before calculating the horizontal winds, and used the same technique to calculate and correct for vertical air motion in the analysis of RASS temperature profiles. Figures 3 and 4 show improvements to standard POP-derived wind and temperature profiles that result from application of MVD.

Fig. 4. Applying MVD to better estimate vertical atmospheric motion leads to improved RASS-measured temperature profilers (right) with respect to profiles computed with vertical motion measured in a standard fashion (left), for four successive radar soundings. The balloon sounding made during radar data acquisition is indicated by the heavy dashed line,

Profiles of various quantities derived solely from radar signatures (after editing out false targets in the spectra and application of MVD) for three successive cycles of the radar beams that occurred during a single balloon ascent are presented in Fig. 5. The right-most profiles of $d\Phi/dz$ include values calculated independently from balloon data (dashed line) for comparison. The consistency of the derived radar profiles and the good agreement with the balloon profiles are encouraging and suggest that the information content of radar wind profiler signals is sufficient to calculate useful profiles of refractive index gradients. Much work remains to make such calculations routine and operational, however, because human judgement is still required to edit out false targets in contaminated spectra. Please note that we did not discuss other important concerns, such as how compensation was made for radar beam broadening, the determination of important atmospheric constants such as temperature or velocity length scales, gradient sign ambiguity, or the extension of the technique to non-stable atmospheres as described by Gossard et al. [in publication, 1997].
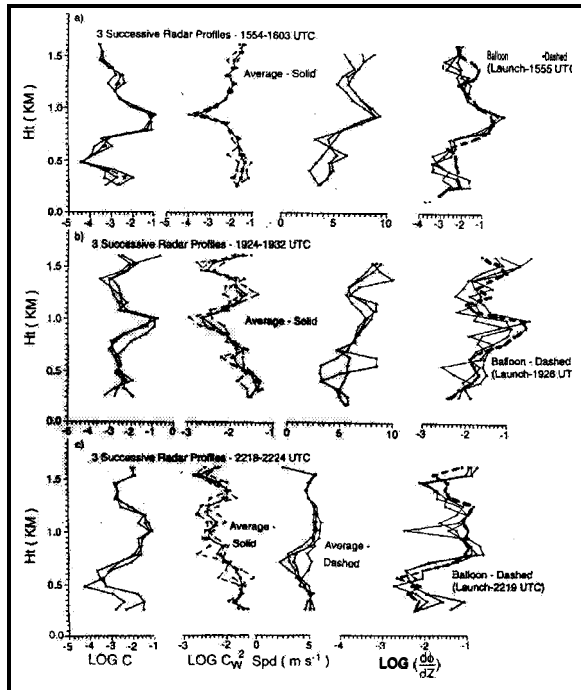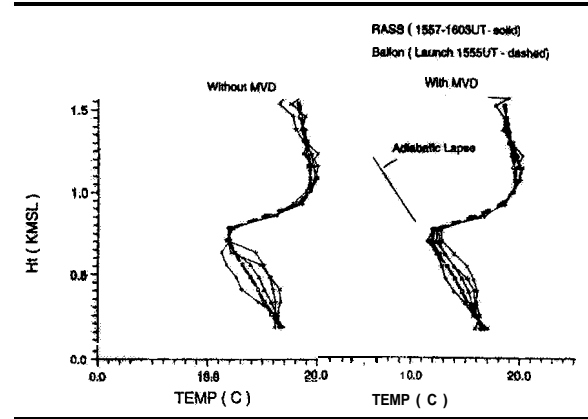

Fig. 5. Profiles (from left to right) of refractive index structure parameter, vertical velocity structure parameter, horizontal wind speed, and gradient of refractivity, for three sets of three successive radar measurements. The right-most profiles of refractivity gradients also inchrde profiles computed from a balloon sounding whose ascent time was comparable to the period of time it took to make the radar measurements.

Humidity Gradients

For subjective analyses, humidity profiles are of more use to meteorologists than refractive index gradients. However, we know that the gradient of humidity is closely related to refractivity through the equation

$$\frac{dQ}{dz} = \frac{1}{b}\frac{d\Phi}{dz} + \frac{a}{b}\frac{d\theta}{dz}$$

Here $d\theta/dz$ is the gradient of potential temperature θ with height, which can be measured well by the same radar using RASS, and *a* and *b are* physical constants. Fig. 6 shows profiles of the graident of humidity derived solely by radar, and derived by balloon. Again, the degree of correlation between these independent profiles gives us hope that the radar alone might someday be able to operationally measure humidity gradients. Then, if the radar's measurements are combined with a measurement of surface humidity and a measurement of IPW, e.g., by inexpensive Global Positioning System (GPS) techrtiques [Rocken et al., 1993, Gutman et al., 1995], one could potentially integrate the radar-derived humidity gradients with sufficient constraint to obtain profiles of humidity in the boundary layer (and above), where most atmospheric water vapor resides.
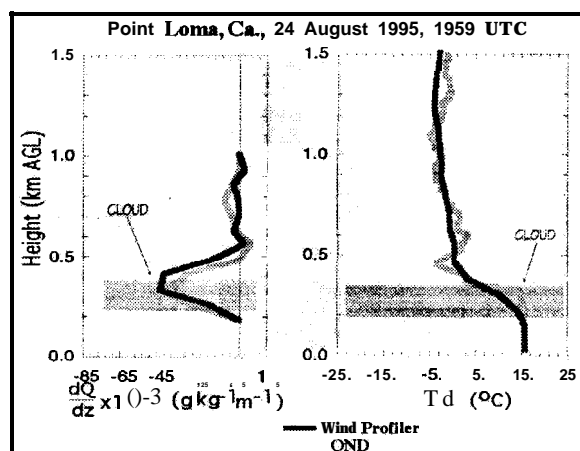

Fig. 6. Gradients of humidity calculated solely by radar and by balloon, in the presence of clouds. Clouds would prevent similar measurements by lidar above cloud base. Combined with a surface measurement of humidity and a GPS measurement of integrated humidity, both inexpensive additions to the radar, continuous all-weather profiling of boundary layer humidity would be possible, with temporal resolution of a few minutes.

Summary

We have conducted an experiment to assess the ability of a 449 MHz radar wind profiler to measure gradients of refractivity, and are encouraged by the results obtained when strong gradients were present. However, advances in automatic signal processing are required to make the technique operationally feasible, because current standard wind profiler spectral moment products are too inaccurate to use without considerable editing and averaging, because spectral contamination is often encountered. Once gradients of refractivity are calculated accurately, it is possible to combine them with other measurements to obtain profiles of humidity throughout the boundary layer (and above). For input to numerical weather forecast models, however, direct assimilation of radar-observed refractive index or humidity gradients may prove most useful.

References

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